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## The impact of dust and ionization effects on abundance measurements of Damped Ly $\alpha$ systems

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**Abstract.** Studies of elemental abundances are a fundamental tool for unveiling the nature of the high-redshift (proto-)galaxies associated to Damped Ly  $\alpha$  systems (DLAs). The present contribution analyses the impact of dust and ionization effects on abundance measurements in DLAs. The behaviour of the  $\alpha/\text{Fe}$  abundance ratio corrected for such effects is used to derive information on the chemical history and nature of DLA galaxies. The  $\alpha/\text{Fe}$  data indicate that DLAs at  $z \approx 2.5$  do not represent a homogeneous class of objects. On average, DLAs show non-enhanced  $\alpha/\text{Fe}$  ratios at low metallicity, suggesting an origin in galaxies with low or intermittent star formation rates.

### 1. Introduction

Damped Ly  $\alpha$  systems (DLAs) have the highest HI column densities among QSO absorbers ( $N(\text{HI}) \geq 2 \times 10^{20} \text{ atoms cm}^{-2}$ ) and contain the bulk of neutral gas observed at  $z \approx 2.5$ . The first studies of the baryonic content in DLAs suggested that their co-moving mass density,  $\Omega_{\text{DLAs}}(z)$ , increases with  $z$  and that  $\Omega_{\text{DLAs}}(z \approx 2.5)$  is comparable to the baryonic density of visible matter in local galaxies,  $\Omega_{\text{stars}}(z = 0)$  (Wolfe et al. 1995). These results lead to the proposal that DLAs represent the gas of high redshift (proto-)galaxies which is consumed in the course of the cosmic evolution because it is transformed into stars. Recent results do not confirm the evolution of  $\Omega_{\text{DLAs}}(z)$  (Rao & Turnshek 2000) and indicate that  $\Omega_{\text{DLAs}}(z \simeq 2.5) < \Omega_{\text{stars}}(z = 0)$  (Storrie-Lombardi & Wolfe 2000, Péroux et al. 2001). However, there is still a general consensus, based on photometric and spectroscopic observations, that DLAs originate in the diffuse gas of (proto-)galaxies. One of the main goals of DLA research is to understand the role of the associated galaxies in the general context of the high redshift universe. At  $z \lesssim 1$  photometric studies indicate that the candidate DLA galaxies have different morphologies and luminosities, with spirals being a small fraction of the sample (Le Brun et al. 1997, Turnshek et al. 2001 and refs. therein). At higher redshift the photometric identification of the intervening galaxies is more difficult and only preliminary results are currently available (Warren et al. 2001). Spectroscopy is the most powerful tool for understanding the nature of DLAs at  $z \geq 2$ , the range where DLAs can be identified and investigated with ground based facilities. In particular, spectroscopy has been used to study the kinematics and the abundances. The kinematical data are useful for probing semi-analytical models of galaxy formation in the context of different cosmog-

nies, but are not able to distinguish between an origin of DLAs in massive disks or in low-mass proto-galactic clumps (Prochaska & Wolfe 1997; Haehnelt, Steinmetz & Rauch 1998; Wolfe & Prochaska 2000b). The elemental abundances can be used to probe the chemical evolution state of DLAs from the comparison with the abundances observed in metal-poor astrophysical sites and with the predictions of galactic evolution models. However, the interpretation of DLAs abundances can lead to rather different conclusions depending on whether dust and ionization corrections are considered to be important or not. For instance, the overabundances of the Si/Fe ratio measured in DLAs have been ascribed to nucleosynthetic processes (Lu et al. 1996), to differential dust depletion (Vladilo 1998; hereafter V98), and to ionization effects (Izotov, Schaerer & Charbonnel 2001). The present contribution summarizes the studies of ionization and dust effects in DLAs (Sections 2 and 3, respectively) and the behaviour of the  $\alpha$ /Fe ratio corrected for such effects (Section 4).

## 2. Ionization effects

The majority of the metal species observed in DLAs is in the ionization state typical of interstellar HI regions. In such regions most of the elements are singly ionized (e.g. C II, Mg II, Al II, Si II, S II, Cr II, Mn II, Fe II, Ni II and Zn II) and only those with ionization potential  $IP_1 > 13.6$  eV are in the neutral state (e.g. N I, O I, and Ar I). This can be understood assuming that HI regions are exposed to a radiation field, the photoionization of species with  $IP < 13.6$  eV being more efficient than competing processes. Column density studies suggest that these conditions hold in DLAs where, for instance,  $N(\text{Mg II}) \gg N(\text{Mg I})$ ,  $N(\text{C II}) \gg N(\text{C I})$ , and  $N(\text{Al II}) > N(\text{Al III})$  (Lu et al. 1996, Prochaska & Wolfe 1999). Studies of the absorption profiles indicate that the typical HI species listed above have very similar radial velocity distributions, consistent with a common origin in HI regions (Lu et al. 1996, Wolfe & Prochaska 2000a). Taken together, these results justify the habit of deriving abundances of DLAs from the species of low ionization without applying ionization corrections. In fact, early computations of the ionization balance in DLAs confirmed that ionization effects are, in general, small or negligible (Viegas 1995; Lu et al. 1995; Prochaska & Wolfe 1996). However, the observations also reveal species in higher states of ionization at the same redshift of the DLAs, such as Al III, C IV and Si IV. The radial velocity profiles suggest that C IV and Si IV originate in volumes of space physically distinct from those occupied by HI regions (Wolfe & Prochaska 2000a). The C IV/Si IV regions are not expected to affect abundance determinations since they do not contribute to the column densities of the HI species. The radial velocity profiles of Al III suggest instead a common origin with the species of lower ionization (Wolfe & Prochaska 2000a). This fact is not easy to understand in the framework of the simple model of a HI region exposed to ionizing radiation and has stimulated new investigations on the ionization balance of DLAs (Howk & Sembach 1999; Izotov et al. 2001; Vladilo et al. 2001; hereafter VCBH01). Considering that Al III requires photons with  $h\nu > 18.8$  eV to be produced, two hypothesis for its origin can be envisaged:

- (1) The Al III arises in the same region where the typical HI species are located. This can be the case if the ionizing continuum is hard and there

are enough high energy photons that can leak into the neutral region (the HI photoionization cross-section declines as  $\nu^{-3}$ ). Ionization models built in the framework of this hypothesis are characterized by a single region embedded in a hard continuum (called hereafter "1H models").

- (2) The Al III arises in a partially ionized interface at the border of the HI region. This can happen if the ionizing continuum is soft, in which case there are not enough energetic photons that can penetrate the neutral region. The neutral region contains the typical HI species, but not Al III. Ionization models built in the framework of this hypothesis are characterized by two regions and a soft continuum ("2S models").

Whatever the origin of Al III is, we expect that other species of moderate ionization, such as Si III or Fe III, can be similarly produced. Unfortunately these species are difficult to detect in DLAs. As a consequence, the ratio  $R(\text{Al III}/\text{Al II}) \equiv N(\text{Al III})/N(\text{Al II})$  is a unique diagnostic tool to probe models of DLA photoionization. Computations constrained by the  $R(\text{Al III}/\text{Al II})$  ratio were first performed for two individual DLAs (Lu et al. 1995; Prochaska & Wolfe 1996). In both cases "1H models" were adopted and the ionization effects were found to be small or negligible. In order to assess the general importance of ionization effects it is therefore necessary to determine  $R(\text{Al III}/\text{Al II})$  in a large number of DLAs and to consider "2S models" as well as "1H models". Unfortunately, the Al II lines are often saturated and only a few accurate determinations of  $R(\text{Al III}/\text{Al II})$  exist. To bypass this problem VCBH01 estimated  $N(\text{Al II})$  indirectly from an empirical correlation found to exist between Si II, Al II, and Fe II column densities. As a result, a sample of 20  $R(\text{Al III}/\text{Al II})$  determinations was obtained. As shown in Fig. 1 (left panel), the ratio is anti-correlated with the HI column density. This trend can be easily reproduced by means of "2S models" computed at constant values of the photoionization parameter  $U$  (i.e. the number of ionizing photons per hydrogen atom). The trend can also be reproduced by means of "1H models", assuming that  $U$  scales with a law of the type  $U \propto N(\text{HI})^{-1.5}$ . In any case the anti-correlation between  $\log R(\text{Al III}/\text{Al II})$  and  $\log N(\text{HI})$  is a powerful constraint for estimating ionization corrections<sup>1</sup>. Examples of correction terms estimated in this way are shown in Fig. 1 (right panel). The ionization corrections are generally small and tend to become less and less important with increasing  $N(\text{HI})$  no matter if one uses 1H or 2S models. It is important to note that the ionized interface and the neutral region are taken to have similar metallicities in the VCBH01 models. Assuming that the ionized region has been enriched by metals while the neutral region is essentially free of metals Izotov et al. (2001) found that ionization corrections can be quite large. With the possible exceptions of specific DLAs where these particular conditions might hold, the ionization corrections are small or negligible for the elements most commonly measured in DLAs.

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<sup>1</sup> The correction term  $C(\text{X}/\text{Y})$  is defined here in such a way that  $(\text{X}/\text{Y})_c = C(\text{X}/\text{Y}) [N(\text{X}^{i_d})/N(\text{Y}^{i_d})]$ , where  $(\text{X}/\text{Y})_c$  is the abundance corrected for ionization effects and  $N(\text{X}^{i_d})/N(\text{Y}^{i_d})$  is the measured column density ratio of the dominant states of ionization.

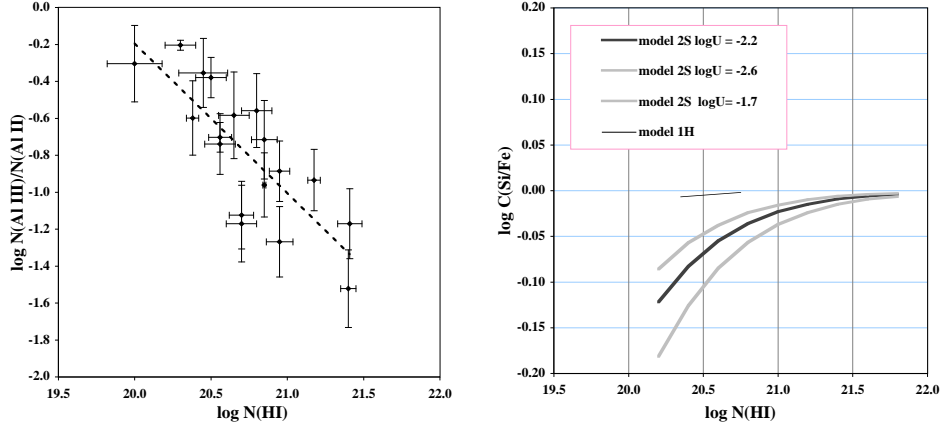


Figure 1. **Left panel:** column density ratio  $N(\text{Al III})/N(\text{Al II})$  in DLAs plotted versus HI column density taken from the compilation by VCBH01. The dashed line represents the linear regression through the observed data points. **Right panel:** Ionization correction term for the Si/Fe abundance ratio in DLAs predicted by 2S models (thick curves) and 1H models (thin curve) computed by VCBH01. These models have been constrained by the requirement to match the trend between  $N(\text{Al III})/N(\text{Al II})$  and  $N(\text{HI})$  shown in the left panel.

### 3. Dust effects

Local interstellar studies indicate that a fraction of the elements is not detected in the gas phase because it is locked into dust grains, an effect referred to as "elemental depletion" (Savage & Sembach 1996 and refs. therein). The fraction in dust varies for different elements, being close to unity for refractory elements, and changes in different interstellar environments, being the highest in cold, dense clouds. If dust is present in DLAs we expect elemental depletion to affect the abundance determinations, in particular those of refractory elements. Two independent types of observations suggest that dust is present in DLAs. On the one hand, QSOs with foreground DLAs have optical spectral indices different from QSOs without foreground DLAs, suggestive of reddening due to the intervening absorbers (Pei, Fall & Bechtold 1991). On the other hand, the relative abundances Zn/Fe and Zn/Cr in DLAs show significant deviations from the corresponding solar values. Such deviations are hard to explain as intrinsic nucleosynthetic effects and can instead be interpreted in terms of differential dust depletion (Pettini et al. 1997). In addition, Hou et al. (2001) claim that the ratios of refractory elements over Zn (e.g. Fe/Zn, Cr/Zn, Si/Zn, etc.) are anti-correlated with the metal column densities and consider this result as an unambiguous sign of dust depletion.

Different approaches are used to bypass the problem of dust depletion. One is to avoid the use of refractory elements (e.g. Fe, Cr, Ni) and to use instead elements essentially undepleted, such as N (Lu et al. 1998, Centuri3n et al. 1998), O (Molaro et al. 2000), S (Centuri3n et al. 2000), and Zn (Pettini et al. 1997, 1999; Vladilo 2000). Another approach is to study DLAs apparently

free of dust. For instance, the  $z = 3.390$  system toward Q0000-26 does not show any evidence of differential Zn/Fe depletion and its detailed analysis has allowed the chemical properties of the associated galaxy to be determined (Molaro et al. 2000). These studies which bypass the depletion problems do not require any assumption on the dust properties, but their application is limited to some elements and to particular DLAs. The only way to perform a general study of DLA abundances is to quantify the depletion effects.

A basic approach to estimate the depletions is to compare the abundance patterns observed in DLAs with the interstellar depletion patterns typical of our Galaxy. Studies of this type indicate that depletions in DLAs resemble those measured in the warm gas of the halo or disk of the Milky Way (Lauroesch et al. 1996; Kulkarni, Fall & Truran 1997). A similar conclusion was obtained by Savaglio, Panagia & Stiavelli (2000), who derived the dust-corrected metallicity of individual systems assuming that the intrinsic abundance ratios of DLAs are solar.

A method for deriving dust-corrected abundance ratios of individual systems without making *a priori* assumptions on the abundance pattern of DLAs was presented by V98. In that method the dust was assumed to have the same composition as the dust in Galactic warm gas; the dust-to-gas ratio of individual DLAs was then estimated assuming that the observed overabundances of Zn/Fe are entirely due to differential depletion. A limitation of that method is that the dust composition is taken to be constant. In addition, some recent investigations indicate that it may be risky to assume  $[\text{Zn/Fe}] = 0$  (Umeda & Nomoto 2001 and refs. therein)<sup>2</sup>. For these reasons a refined procedure for dust correction has been recently developed (Vladilo 2001, in preparation). A preliminary presentation of such procedure is given in the rest of this section. The fraction in dust of an element X,  $f_X$ , is allowed to vary as a function of the dust-to-metals ratio,  $\rho$ , and of the intrinsic abundances of the medium,  $(X/Y)_{\text{int}}$ , according to an analytical expression of the type

$$f_X \propto \rho^{(1+\eta_X)} 10^{(\varepsilon_X-1)[\frac{X}{Y}]_{\text{int}}} , \quad (1)$$

where Y is an element used as a reference for abundance measurements. This expression is a generalization of Eq. (11) given in V98, which represents the case  $\eta_X = 0$  and  $\varepsilon_X = 0$ . The parameters  $\eta_X$  can be calibrated using the depletion patterns observed in the Galaxy, where  $[X/Y]_{\text{int}} = 0$ . With such a calibration all the typical depletion patterns of the Milky Way can be successfully reproduced by only varying  $\rho$  (Fig. 2, left panel). The parameters  $\varepsilon_X$  describe the dependence of the dust composition on the composition of the medium (gas plus dust). These parameters are expected to be in the range  $0 \leq \varepsilon_X \leq 1$  and can potentially be calibrated by studying depletion patterns in galaxies with non-solar abundances. The possibility that the intrinsic Zn/Fe ratio in DLAs differs from the solar value is considered in a self-consistent way in Eq. (1). By following the same logical steps described in V98 it is possible to derive (i) an expression for estimating  $\rho$  given the observed  $[\text{Zn/Fe}]$  and a guess of  $[\text{Zn/Fe}]_{\text{int}}$ ; (ii) an expression for correcting abundance ratios given  $\rho$ . This two-step procedure can be repeated for different values of  $\varepsilon_X$  and  $[\text{Zn/Fe}]_{\text{int}}$  and the corrected

<sup>2</sup> The usual definition  $[X/Y] \equiv \log [N(X)/N(Y)] - \log (X/Y)_{\odot}$  is adopted.

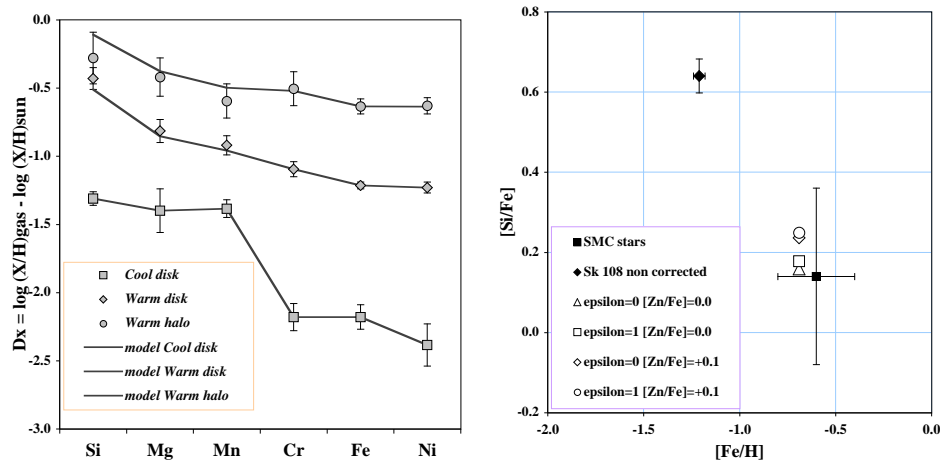


Figure 2. **Left panel:** observed and predicted Milky Way depletions. Symbols: observed depletions in the cold disk (squares), warm disk (diamonds) and warm halo (circles) (Savage & Sembach 1996). Lines: depletion patterns modeled with Eq. (1). **Right panel:** dust correction of the [Si/Fe] ratio measured in the SMC interstellar gas towards Sk 108 (Welty et al. 1997). Filled diamond: [Si/Fe] versus [Fe/H] not corrected for dust. Empty symbols: dust-corrected [Si/Fe] ratios plotted versus [Zn/H] (see legend). Filled square: range of [Si/Fe] and [Fe/H] measurements typical of SMC stars (Russell & Dopita 1992).

abundances estimated in each case. An example of application of this procedure to the [Si/Fe] ratio in the SMC interstellar gas towards Sk 108 is shown in Fig.2 (right panel). The SMC interstellar ratio is clearly affected by depletion since it appears to be much more enhanced than in SMC stars. The [Si/Fe] corrected for dust closely matches the expected stellar values. The [Zn/H] ratio is in good agreement with the SMC stellar metallicities, while the [Fe/H] ratio badly underestimates the metallicity. This example illustrates the capability of the dust correction procedure to recover the intrinsic abundances and indicates that the [Fe/H] ratio should not be used as a metallicity indicator. An example of application of the revised dust correction procedure in DLAs is presented in the next section.

#### 4. The $\alpha$ /Fe ratio in DLAs

Observations of metal-poor stars of the Milky Way indicate that the ratio of  $\alpha$ -capture over iron-peak elements is overabundant ( $[\alpha/\text{Fe}] \approx +0.5$  dex at  $[\text{Fe}/\text{H}] \simeq -2/-3$  dex) and that the overabundance declines with increasing metallicity (Ryan, Norris & Beers 1996 and refs. therein). This behaviour of the  $\alpha$ /Fe ratio is interpreted in terms of the so-called *time-delayed model*, based on different timescales of production of  $\alpha$ -capture over iron-peak elements by SNe II and SNe Ia (Matteucci 2000 and refs. therein). The  $\alpha$ /Fe ratio is therefore an indicator of chemical evolution that can also be applied to infer the evolutionary state

of DLA galaxies. Here we briefly discuss the  $[\text{Si}/\text{Fe}]$  ratio, the most commonly measured  $\alpha/\text{Fe}$  ratio in DLAs, taking into account the effects of ionization and dust.

The ionization effects act in such a way that  $[\text{Si}/\text{Fe}]$  tends to be overestimated in DLAs and a negative correction must be applied to recover the intrinsic abundance (Fig. 1, right panel). The effect, however, is very small independent of the ionizing continuum adopted, provided the gas sampled along the line of sight is chemically homogeneous. Therefore we consider  $[\text{Si}/\text{Fe}]$  ionization corrections to be negligible in the rest of this discussion. Dust depletion yields an enhanced  $[\text{Si}/\text{Fe}]$  ratio in the local ISM (Savage & Sembach 1996). As discussed in Section 3, dust depletion can significantly affect the  $\text{Si}/\text{Fe}$  in a metal-poor galaxy such as the SMC (Fig. 2, right panel) and is likely to influence the measurements in DLAs. The original claim that  $[\text{Si}/\text{Fe}]$  is enhanced in DLAs due to nucleosynthetic processes (Lu et al. 1996) must be therefore taken with extreme caution. In Fig. 3 we show an updated collection of  $[\text{Si}/\text{Fe}]$  measurements in DLAs corrected for dust with the procedure outlined in the previous section. Two conclusions can be derived from a quick look at the dust corrected  $[\text{Si}/\text{Fe}]$  data shown in the figure: (1) the decline with increasing metallicity expected by the *time-delayed model* is not detected at a significant level of statistics, even though the dashed line resulting from the linear regression through the data is consistent with the existence of such a trend; (2) most of the DLAs ratios lie below the typical  $[\text{Si}/\text{Fe}]$  values measured in metal-poor Galactic stars (continuous line). Both conclusions are fairly independent of the parameters adopted in the dust correction procedure (see caption to Fig. 3). In addition, both conclusions are supported by a study of the  $[\text{S}/\text{Zn}]$  ratio, a dust-free indicator of the  $\alpha/\text{Fe}$  ratio in DLAs (Centurión et al. 2000). The consistency of the results found from dust corrected  $[\text{Si}/\text{Fe}]$  ratios and dust-free  $[\text{S}/\text{Zn}]$  ratios is an argument in favour of the general accuracy of the dust correction procedure. Independent evidence of non enhanced  $\alpha/\text{Fe}$  ratios at very low metallicity is found in the dust-free system at  $z = 3.3901$  towards Q0000-26 (Molaro et al. 2000).

The lack of a clear trend of the  $\alpha/\text{Fe}$  ratio with increasing metallicity is not too surprising considering that DLAs are probably associated to galaxies of different morphology and evolutionary status. We note, however, that the modest decrease with metallicity, although not statistically significant, is seen both in  $[\text{Si}/\text{Fe}]$  and  $[\text{S}/\text{Zn}]$ . In addition, the linear regression of the same data versus redshift suggests a modest decrease of both  $[\text{Si}/\text{Fe}]$  and  $[\text{S}/\text{Zn}]$  ratios with cosmic time. These trends with redshift, although not statistically significant, are also consistent with the general expectations of the *time delayed model*.

The relatively low  $\alpha/\text{Fe}$  values found in DLAs compared to those measured in Galactic stars of similar metallicity indicates that DLAs have undergone a chemical evolution different from that of the solar neighbourhood. The lower  $\alpha/\text{Fe}$  ratios at a given metallicity can be explained by chemical evolution models with low or intermittent star formation rates (Matteucci 1991). From this kind of argument an origin of DLAs in low-mass galaxies seems more appropriate than an origin in progenitors of galaxies as massive as the Milky Way. This conclusion challenges the original idea that DLAs are progenitors of massive rotating disks. It is important to remark, however, that some DLAs do show evidence for a  $\alpha/\text{Fe}$  enhancement, the most clear example being the  $z = 3.025$  absorber

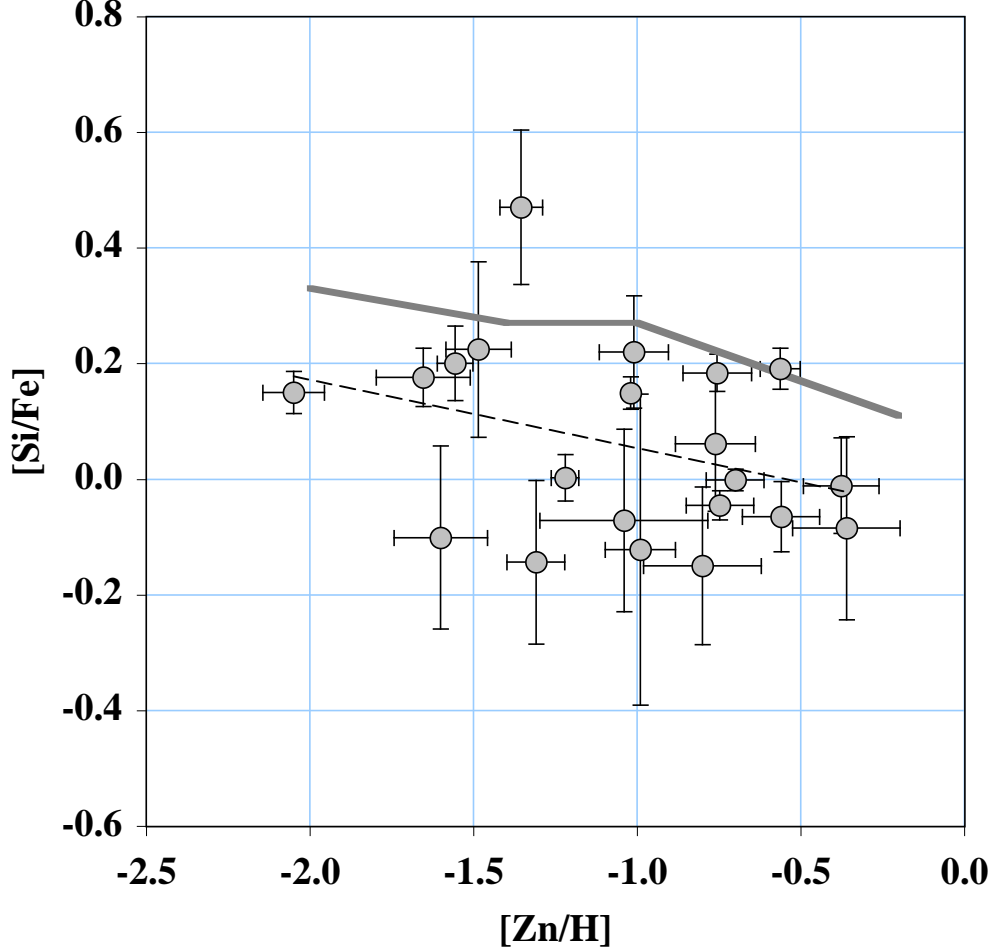


Figure 3. Compilation of available  $[\text{Si}/\text{Fe}]$  and  $[\text{Zn}/\text{H}]$  measurements in DLAs corrected for dust depletion as explained in Section 3. Most of the original data are taken from Prochaska & Wolfe (1999); the most enhanced  $[\text{Si}/\text{Fe}]$  ratio at  $[\text{Zn}/\text{H}] = -1.4$  corresponds to the  $z = 3.025$  absorber towards Q0347-38 (Levshakov et al. 2001); a complete list of references will be presented in a subsequent work. Dotted line: linear regression through the corrected data. Thick curve: mid-mean vector of the  $[\text{Si}/\text{Fe}]$  measurements in Galactic metal-poor stars defined by Ryan et al. (1996). The parameters adopted in the dust correction procedure are  $\varepsilon_x = 1$  and  $[\text{Zn}/\text{Fe}]_{\text{int}} = 0.0$ . By varying the input parameters in the ranges  $0 \leq \varepsilon_x \leq 1$  and  $0.0 \leq [\text{Zn}/\text{Fe}]_{\text{int}} \leq +0.1$  the  $[\text{Si}/\text{Fe}]$  corrected ratios still lie below the thick curve and show a hint of a decline with increasing  $[\text{Zn}/\text{H}]$ .



towards Q0347-38 (Levshakov et al. 2001), also shown in Fig. 3. This counter-example indicates that DLAs include galaxies with different chemical evolution and therefore that they do not represent a homogeneous class of galaxies.

## 5. Conclusions

Abundance studies provide unique information on the nucleosynthetic processes and chemical evolution at work in DLAs provided we are able to disentangle dust and ionization effects. Ionization corrections could be large if the bulk of the neutral gas is metal poor while the metal lines originate in a HII region. This might happen in specific cases, but is probably not the rule. In general, the ionization corrections are expected to be small and to become even smaller with increasing  $N(\text{HI})$  for most of the elements commonly measured. On the other hand, dust depletion can significantly affect DLAs abundance determinations. Exceptions are the non-refractory elements, such as N, O, S and Zn. While some information can be gathered from the analysis of these elements, the study of the overall abundance pattern requires dust corrections to be applied. A revised method for dust correction has been briefly outlined in this presentation. This method allows the dust composition to vary and as a function of the dust-to-gas ratio and, for the first time, as a function of the abundance of the medium (dust plus gas). This dust correction method has been successfully tested in the interstellar gas of the SMC and applied to correct Si/Fe measurements in DLAs. The dust-corrected [Si/Fe] ratios suggest that most DLAs have undergone a chemical history different from that observed in metal-poor stars of the solar vicinity. This result challenges the concept that DLAs are progenitors of present-day spiral galaxies. An origin in galaxies or proto-galaxies with lower or intermittent rates of star formation is favoured by the  $\alpha/\text{Fe}$  corrected data. The same data indicate that DLAs do not represent a homogeneous class of objects since they include galaxies with different types of chemical evolution. This conclusion is consistent with the well known inhomogeneity of the DLAs galaxies identified at  $z \lesssim 1$ . The decline of the  $\alpha/\text{Fe}$  ratio expected by *time-delayed* models of chemical evolution is not detected clearly, probably as a consequence of the inhomogeneity of the sample.

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